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In-Cloud Turbulence Structure of Marine Stratocumulus at Pt. Reyes, CA, during MASRAD

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This study quantifies the level of turbulence inside the marine stratocumulus cloud deck over Pt. Reyes, CA, during the Marine Stratus Radiation, Aerosol, and Drizzle Experiment (MASRAD) in July 2005, and identifies the dominant sources of turbulent kinetic energy. For our analysis we used vertical velocity data from a 3-mm wavelength (94-GHz) vertical pointing Doppler radar in combination with collocated radiosonde data. The results showed that the stratocumulus deck at Pt. Reyes behaved differently from what has been found in previous studies. In particular, we found a decrease of turbulence levels with height within the cloud both during day and during night. The analysis highlights that for the conditions of our study longwave radiative cooling at cloud top was compensated by a number of mechanisms, resulting in the observed profiles. The production of turbulent kinetic energy is dominantly driven by wind shear.

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1. Introduction

The life cycle and the structure of stratocumulus clouds are closely related to the in-cloud turbulence and its interactions with the surrounding environment (e.g. *Driedonks and Duynkerke* [1989]). Previous observations found longwave radiative cooling at cloud top to be the dominant mechanism in generating turbulent kinetic energy [*Lilly*, 1968] either throughout the whole boundary layer (e.g. *Nicholls* [1989]), or within the cloud layer [*Frisch et al.*, 1995]. During the day time, shortwave warming from solar radiation compensates more or less the cloud top cooling [*Slingo et al.*, 1982], inducing strong diurnal variations of turbulence in the stratocumulus. Other observational and modeling studies pointed out that rather than longwave cooling at the cloud top, shear could be the dominant mechanisms in generating turbulence [*Brost et al.*, 1982a, b; *Moeng*, 1986]. The characteristics of the radiatively driven and shear driven boundary layer could be significantly different from each other.

In recent years millimeter wavelength radars have been successfully used to provide information about in-cloud motion by tracking the movement of cloud droplets [*Kollias and Albrecht*, 2000; *Kollias et al.*, 2007; *Babb and Verlinde*, 1999; *Albrecht et al.*, 1995]. Cloud radars have the advantage of providing vertically resolved data that are continuous in time, thus enabling the study of diurnal variation of cloud properties.

In this paper we present a study of marine stratocumulus clouds at Pt. Reyes, CA, for July 2005 using data of vertical velocity obtained by a 3-mm vertical pointing cloud radar. The radar was deployed during the Marine Stratus Radiation, Aerosol and Drizzle Experiment (MASRAD), operated by the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Program. Compared to other studies (e.g. *Frisch et al.* [1995] or *Albrecht et al.* [1988]) the cloud deck under investigation was thin, with cloud thicknesses ranging from 50 m to 350 m. This fact, combined with a low cloud base between nearly 0 m to 200 m above ground and strong wind shear made this a unique study of stratocumulus clouds. In Section 2 we outline the method for quantifying the spatial and temporal evolution of turbulence inside the marine stratocumulus cloud deck. In Section 3 we present the overall statistics for the month of July. For a specific day (July 5) we show the vertical profiles and diurnal variation of turbulence activity. Section 4 discusses the possible mechanisms that lead to the observed spatial and temporal development of turbulence kinetic energy within the cloud. We conclude our findings in Section 5.

2. Data and Methodology

We used 3-mm-wavelength radar data from the whole month of July 2005, consisting of vertical velocity time series in cloudy air at various levels. The raw data have a temporal resolution of about 2 seconds, and a vertical resolution of 30 m. The uncertainty of the vertical velocity measurements is on the order of xx $\mathrm{cm\,s^{-1}}$ [*Kollias and Albrecht*, 2000]. The cloud base was measured by a Vaisala ceilometer (15 m resolution) and the cloud top retrieved by the reflectivity of the cloud radar (30 m resolution). Radiosonde soundings, released four times daily at the same location as the cloud radar were also used in the analysis. The soundings showed that for the month of July 2005 the prevalent wind directions in the boundary layer at the site ranged between southwest to north and the radar sampled air masses ranged from continental to marine. We used the radiative model RRTM (Rapid Radiative Transfer Model, *Mlawer et al.* [1997]; *Clough et al.* [2005])

to determine the magnitude of radiative cooling at the cloud top with the atmospheric profiles, cloud liquid water path (LWP) and effective radius (r_e) as model input.

Similar to previous studies [*Frisch et al.*, 1995; *Kollias and Albrecht*, 2000; *Babb and Verlinde*, 1999; *Hignett*, 1991], we used the standard deviation of the vertical velocity to quantify the turbulence inside the cloud. We determined an appropriate averaging period, so that the turbulent scales are included, but the mesoscale scales are excluded, by calculating the power spectra of the vertical velocity time series. The results for various time series (day, night, various height levels) showed that 24 min is the time interval that separates the mesoscale and the turbulent scale. We therefore divided the vertical velocity time series in successive intervals of 24 min and calculated for each interval the mean, $\overline{w}$, the standard deviation, σ_w, and the skewness, S_w. These statistical quantities are functions of time and height. For our analysis we generally removed data whenever drizzle was reported (see supplemental information for the details of this procedure). The day of our case study, July 5 2005, was a day without drizzle.

3. Results

3.1. Overview of Pt. Reyes stratocumulus clouds during July 2005

During the month of July 2005, there were 21 cloudy days. Among those cloudy days, 12 days were reported to have drizzle, usually associated with thicker clouds. The cloud thickness showed a pronounced diurnal cycle being thickest (200–250 m) during the early morning (03:00–08:00 LST) and becoming gradually thinner during the day, with the cloud frequently dissipating in the afternoon.

To investigate the vertical variation of σ_{w} during July 2005, we separated the cloud in four vertical compartments and calculated σ_{w}-averages for each compartment separating day time and night time as shown in Table 1. For both day and night the σ_{w}-averages decreased with height. This is contrary to many previous studies, which showed a maximum of standard deviation close to the cloud top during the night due to longwave radiative cooling (e.g. *Nicholls* [1984]), and a characteristic diurnal cycle in the turbulence levels due to shortwave warming from solar radiation reducing the turbulence at the cloud top by compensating the longwave cooling [*Frisch et al.*, 1995]. To investigate the reasons for our results in more detail we analyzed a specific day, July 5 2005.

3.2. Case study for July 5 2005

July 5 was chosen because of the persistent deck of stratocumulus without the occurrence of drizzle. Regarding the in-cloud motion it was a typical day for the month of July, i.e. the vertical profiles of σ_{w} on July 5 were comparable to the July averages. The wind direction was from the northwest. The time-height cross-sections of σ_{w} (left) and S_{w} (right) in Figure 1 show that the cloud formed at 5 UTC (22:00 LST on July 4), thickened during the morning of July 5 to about 250 m thickness at 17 UTC (10:00 LST), and dissipated during the afternoon, which is a typical cloud development during the month of July. At cloud top σ_{w} was consistently low with values of about 0.4 $\mathrm{m\,s^{-1}}$ compared to 0.7 $\mathrm{m\,s^{-1}}$ at the cloud base. The corresponding time-height sections of S_{w} were predominantely positive at cloud top indicating more intense and narrower updraft than downdraft in this region of the cloud.

To quantitatively evaluate the evolution of turbulence levels with respect to time of the day and relative height, Figure 2 shows profiles of σ_w and S_w for the night (top), the morning (middle), and the afternoon (bottom). Each panel contains five profiles that together span a period of about 2 hours, displayed as function of relative height with respect to cloud base. The five profiles in each group were chosen so that the third one coincides in time with the soundings discussed later in this paper.

Generally, σ_w decreased with height during both nighttime and daytime. The magnitude of σ_w decreased from night to morning for all the four layers of the cloud by about 0.2 $\mathrm{m\,s^{-1}}$. From morning to afternoon, in the lower part of cloud, σ_w stayed at the same magnitude of about 0.75 $\mathrm{m\,s^{-1}}$, however in the upper part of cloud, the magnitude increased by 0.2 $\mathrm{m\,s^{-1}}$, leading to a decrease in the gradient of σ_w. The panels for S_w show that there were predominantly positive values throughout almost the whole cloud deck for both daytime and nighttime of about 0.3, except for some negative values in the bottom part of the cloud. The skewness profiles in the afternoon were more variable compared to the other two profiles.

4. Discussion

4.1. Radiative cooling at cloud top

Several previous studies found cloud top radiative cooling as the dominant mechanism to cause turbulent mixing in the cloud layer, especially during night time [*Frisch et al.*, 1995; *Hignett*, 1991]. In this case predominantly negative S_w as well as a maximum of σ_w are expected at cloud top. To estimate the magnitude of the cloud top radiative cooling for our case during the night (1127 UTC) and the afternoon (2333 UTC) we carried out

RRTM model calculations as described in Section 2. The resulting net longwave radiative flux is shown in Figure 3, where the LWP is 50 $\mathrm{g\,m^{-2}}$ and 70 $\mathrm{g\,m^{-2}}$ for day and night, respectively, and the effective radius is estimated as 6 μm. It reached about 83 $\mathrm{W\,m^{-2}}$ during the day and about 69 $\mathrm{W\,m^{-2}}$ during the night, which is on the same order of magnitude as those found in *Slingo et al.* [1982] and *Ackerman et al.* [1995]. Hence, we conclude that longwave radiative cooling did take place. To reconcile this finding with the observed variation of σ_{w}, we conclude that there were mechanisms in place that compensated the negative buoyancy generated by cloud top radiative cooling.

4.2. Mechanisms compensating cloud top cooling

The positive values of S_{w} (compare Figures 1 and 2) suggest that strong updraft motions occurred inside the cloud. The sources of energy for such updrafts are usually latent heat release above the lifting condensation level and sensible heat from the lower part of cloud and the surface. Since the cloud deck was rather thin, it seems likely that the latent and sensible heat flux reached the cloud top. This explains why we did not find a spatial separation between the two sources of turbulence generation, the cooling at the cloud top and the latent heat and sensible heat warming from the bottom, which was for instance found in *Frisch et al.* [1995], but rather an overall compensation of cloud top cooling.

In Figure 3 the radiosonde data show that above the top of the stratocumulus, in the temperature inversion layer, the mixing ratio of water vapor increased with height during both day and night. (Note that the atmospheric profile of the morning is not shown as the sounding is not guaranteed to pass throught the cloud.) These local maxima of water vapor mixing ratio could be due to advection of moist air or due to detrainment of saturated cloudy air by in-cloud updraft into the cloud top. The latter is supported by the observed positive skewness at cloud top and is consistent with model simulations by *Sorooshian et al.* [2007] who found that, during MASE, a significant fraction of the aerosol mass concentration above cloud can be accounted for by evaporated droplet residual particles. Regardless of the causes of the moisture maximum, when this moist air is re-entrained, evaporative cooling at cloud top is limited.

The wind shear at Pt. Reyes ranged from 0.01 to 0.04 s^{-1} (Figure 3). This is about a magnitude larger than the values found in *Frisch et al.* [1995], which ranged from 0.002 to 0.01 s^{-1}. The greater magnitude of wind shear is consistent with larger σ_w values compared to other studies [*Frisch et al.*, 1995]. The stronger wind shear inside the cloud and at the cloud top during both day and night has two effects. First, it generates turbulence and enhances entrainment of moist, warm air (compared to in-cloud air) at the cloud top. Second, with stronger turbulence, the latent heat and sensible heat is distributed more effectively from the bottom upwards and therefore compensates the cloud top radiative cooling.

4.3. Temporal evolution of σ_w

While σ_w decreases with height during both day and night, there are slight changes in the absolute magnitude of σ_w on July 5. During morning and afternoon, shortwave radiative warming from solar radiation contributes by compensating the longwave cooling at cloud top. This is consistent with overall smaller values of σ_w during the morning compared to the night as seen in Figure 2. In the afternoon, the gradient of the σ_w profile decreases, most likely due to increased wind shear (Figure 3), which promotes mixing in the in-cloud atmosphere. The overall small temporal variation in σ_w suggests that the in-cloud turbulence over Pt. Reyes is not dominantly radiatively driven, but rather by wind shear and by surface fluxes.

5. Conclusions

Our analysis showed that for the marine stratocumulus at Pt. Reyes during July 2005 the standard deviation of vertical velocity, σ_w, decreased with height, both during day and during night, in contrast to other stratocumulus studies. This suggests that for the prevailing conditions the cloud top longwave cooling, while still present, was compensated by several simultaneously operating mechanisms. The cloud deck was on average only 200 m thick and close to the ground. These facts, in conjunction with the strong in-cloud wind shear, enabled effective transport of latent heat and sensible heat from the lower part of the cloud to the upper part, partly offsetting the radiative cooling at cloud top. Moreover, the air with a local maximum of water vapor mixing ratio above the cloud top did not cause much evaporative cooling when re-entrained. It may therefore have helped offsetting the radiative cooling at the cloud top even further. The cloud top cooling being compensated by these mechanisms thus did not produce strong turbulent motion at the top. Hence, the vertical profiles of σ_w for both day and night generally decreased with height and varied only slightly in magnitude. In contrast to the lack of diurnal cycles in the profiles of σ_w, the cloud thickness did show a pronounced diurnal cycle (see supplementary material for the diurnal change in cloud thickness), which is most likely explained by daytime surface heating over land causing daytime entrainment.

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Table 1. Mean of σ_{w} in $\mathrm{m\,s^{-1}}$ for July 2005 during day and night separated into four vertical layers with Layer 1 being the lowest.

	σ_{w} day	σ_{w} night
Layer 1	0.68 ± 0.23	0.62 ± 0.19
Layer 2	0.63 ± 0.21	0.62 ± 0.25
Layer 3	0.58 ± 0.26	0.59 ± 0.25
Layer 4	0.56 ± 0.30	0.56 ± 0.30

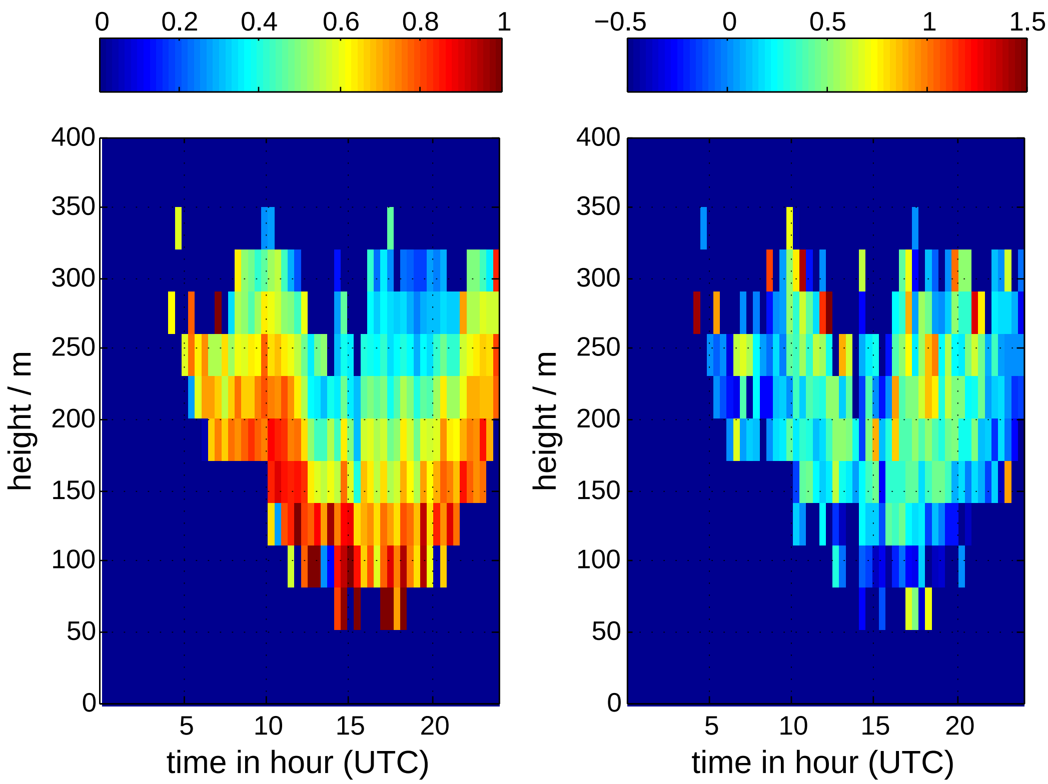

Figure 1. Left: Time-height plot of σ_{w} in $\mathrm{m\,s^{-1}}$ for 5 July, 2005. The color scale is capped at 1 $\mathrm{m\,s^{-1}}$ for better resolution. Right: Time-height plot of S_{w} for 5 July, 2005. The color scale is capped between -0.5 and 1.5 for better resolution. Vertical velocity measured by the 3-mm cloud radar.

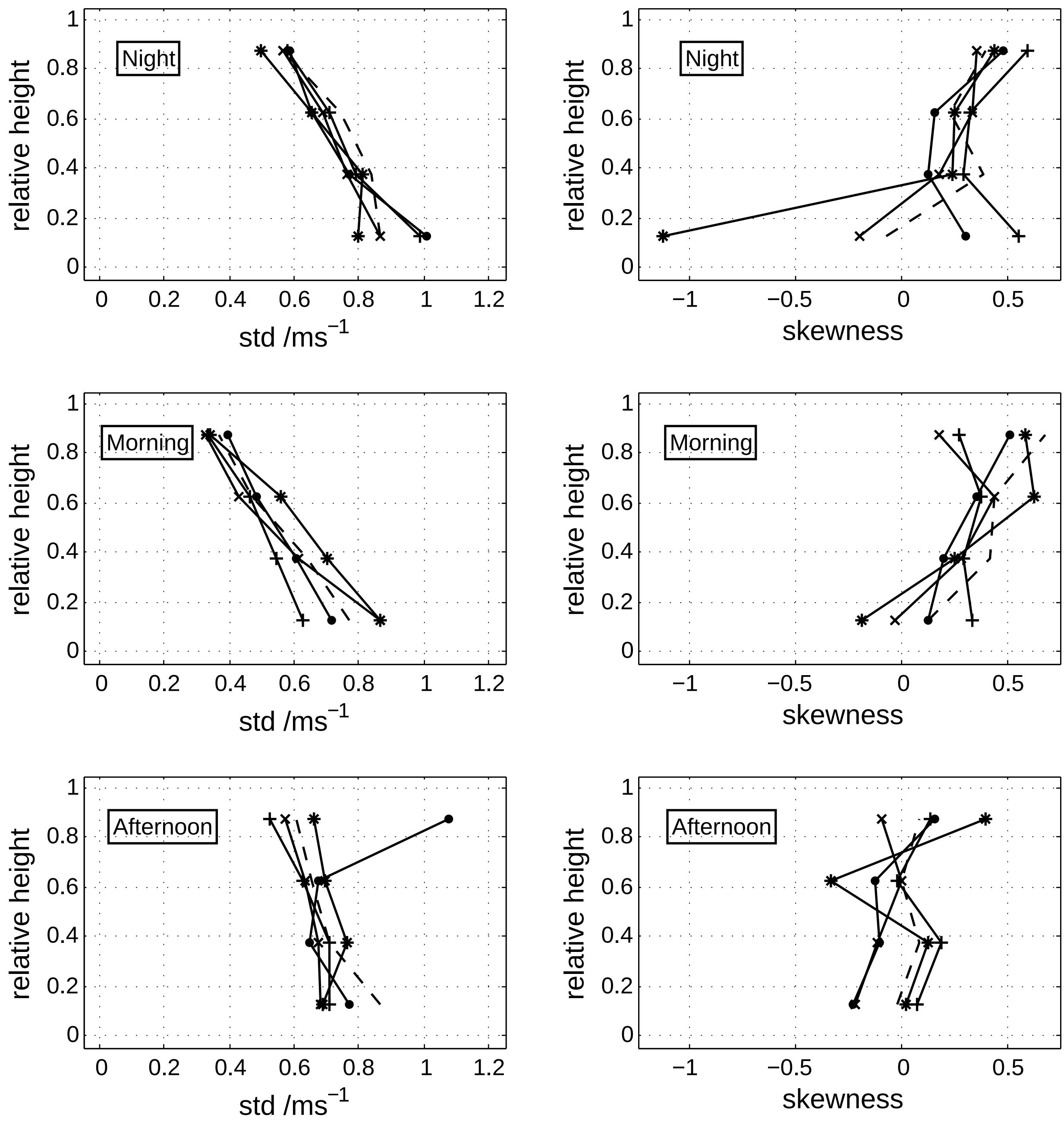

Figure 2. Left panels: Profiles of σ_{w} for 5 July, night (top, 10:24-12:24 UTC), morning (middle, 16:24-18:24 UTC) and afternoon (bottom, 22:24-00:24 (6 July) UTC). Right panels: Profiles of S_{w} for the same 3 periods of time. In each panel, the plus, dash, cross, dot and star represent the first to the fifth 24-min interval, respectively. Vertical velocity measured by the 3-mm cloud radar.

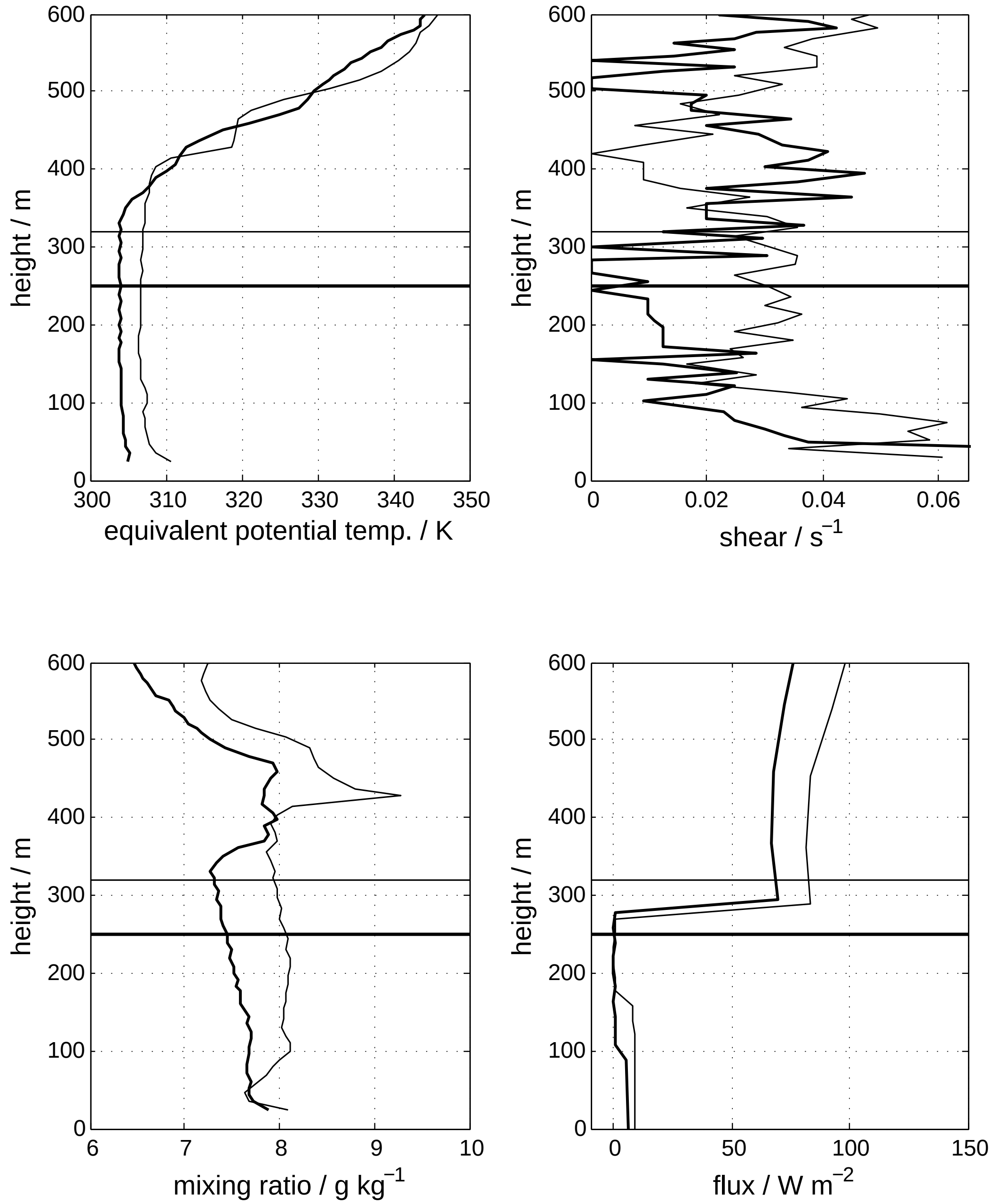

Figure 3. Top left: Equivalent potential temperature. Top right: Wind shear. Bottom left: Water vapor mixing ratio. Variables calculated based on radiosonde data. Bottom right: Net longwave radiative flux (upward minus downward flux) calculated with radiative transfer model RRTM. Thick: 5 July night; Thin: 5 July afternoon. The horizontal lines are averaged cloud base and cloud top from the radar on 5 July.